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Nut-yield variations and yield–diameter relationships in open-canopy black walnut trees in southern USA

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Abstract

Many landowners in the United States have little knowledge of the potential economic returns from agroforestry practices. Economic simulators for temperate agroforestry practices have been generated; yet, there are few data sets on yields of timber and other products to validate and refine such models. The objectives of this study were to characterize variations in nut yields among open canopy eastern black walnut (*Juglans nigra* L.) trees and apply this information to the development of predictive equations between tree diameter at breast height (DBH) and nut yields. Three data sets were analyzed that included results from Tennessee; Chetopa, Kansas; and Mt Vernon, Missouri. Tree-to-tree variation in nut yields was high within each data set, with coefficients of variation for nut yields typically exceeding 50%. Averaging nut yields over several consecutive years reduced coefficients of variation. Nearly half of the high nut producing trees exhibited an alternate, biennial nut bearing pattern. Trees with low average nut yields had either sporadic or irregular patterns of nut bearing. The regression coefficients for equations relating stem diameter and nut yields varied considerably. Averaging nut yields over consecutive years, and averaging stem diameter and nut yields over a number of trees increased regression coefficients of such equations. These results indicate that predicting nut yields of a tree stand over a several year-period will be easier than predicting yields for a specific tree in a specific year.

Introduction

Agroforestry practices are being adopted slowly in the temperate regions of the United States. Recent surveys characterizing attitudes among landowners in Missouri indicate that many landowners have little knowledge of agroforestry practices and in particular are unaware of the potential economic returns from such practices (Raedeke et al. 2003). Economic simulators for temperate agroforestry practices have been generated (New Zealand Forest Research Institute 1994; Thomas et al. 1994; Bergez et al. 1999; Simioni et al. 2000). Few data sets on growth of temperate agroforestry tree species are available to run, validate and refine

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such models. Eastern black walnut (*Juglans nigra* L.) is a valuable tree species in the United States and a prime candidate for agroforestry practices (Garrett and Kurtz 1983) because of its value for timber, nuts for human and wildlife consumption, and nutshells for abrasives. Timber harvests of eastern black walnuts in the United States amount to more than 500,000 m^3 $year^{-1}$ (Schmidt and Kingsley 1997). Commercial United States nut production has averaged 11,000 metric tons annually, with the 2003 harvest exceeding 12,000 metric tons (Hammonds Products Co. 2004).

Sound estimates of nut yields are needed in order to predict the income potential of black walnut agroforestry practices. There are few detailed studies on nut yields of eastern black walnuts. Zarger (1946) reported on the nut yields of over 100 native trees growing in the Tennessee River valley from 1940 to 1946. Trees included in this study were described as being open canopy, i.e. growing without competition from other trees. Relationships between tree stem diameter measured at 1.37 m height (diameter at breast height, DBH) and nut yields have been developed previously from this data set (Kincaide 1982). The use of DBH as a measure of tree productivity at a site, rather than basal area, seems reasonable for the data from Zarger (1946) since these trees were growing in an open canopy or 'free growth' stage. Continued use of DBH as a measure of tree growth for relating to nut yields seems justified in light of two observations. First, in a later report, Zarger (1956) reported that canopy size was highly correlated to DBH for open canopy eastern black walnut trees. Second, Ares and Brauer (2004) found that stand density did not significantly contribute to variations in mean DBH among walnut trees growing in 54 stands in the south central United States. Ares and Brauer (2004) concluded that most of the walnut stands in this study were in a 'free growth' stage or open canopy due to management and/or age. Similarly, native pecan trees growing as a component in agroforestry practices in the same region of the United States are managed to prevent canopy closure (Ares and Brauer 2006). Typically stands of mature pecan trees (i.e. those with DBH > 50 cm) are thinned every few years to maintain tree canopy within a narrow range and to prevent tree canopy closure.

Ares and Brauer (2004) also reported nut yields for 12 black walnut stands for a single year, 2002. These preliminary data indicated that improved varieties had higher nut yields than those predicted from the DBH–nut yield equation developed from Zarger's study. In addition, nut yields were highly variable both within and among stands (Ares and Brauer 2004). Significant variations from year to year in nut yields from the same tree are thought to be common and textbooks say 'Abundant crops are produced irregularly' (Woodroof 1979). Reid et al. (2004) indicated that most varieties of eastern black walnut selected for superior nut quality exhibited an alternate bearing pattern, i.e., 1 year with high yields followed by a year of lower yields. Further information is needed to construct a database by which the economic returns of black walnut agroforestry practices can be predicted. The objectives of this study were to (i) better characterize annual and tree-to-tree variations in nut production by native and improved varieties of eastern black walnut; and (ii) explore more fully the relationship between trunk DBH and nut yields.

Materials and methods

Chetopa data set

Scions of 20 different genotypes selected for improved nut quality were grafted onto native seedling rootstock. Seedling trees were planted in 1987 at Pecan Experiment Field, Kansas State University near Chetopa, Kansas (USA) on the floodplain of the Neosho River. The climate is typically continental, with cold winters and hot summers. Average annual rainfall is 1030 mm and average annual temperature is 14.2 °C. The growing season spans from early April to late October with 200 frost-free days. The soil is a fine, montmorillonitic, thermic Vertic Haplaquoll, Osage series. Trees were planted in rows 9.1 m apart with 9.1 m between trees in each row. Trees received 90 kg N ha^{-1} and anthracnose was controlled with fungicides. The understory was maintained relatively free of competing vegetation by mechanical cultivation. Significant nut production was first noted in 1997. The data set included annual nut production from 1997 to 2001 and DBH data collected in 2001. Tree canopy closure had not occurred by the end of the 2001 growing season.

Mt Vernon data sets

In 1975, eastern black walnut seedlings from 10 different seed sources were planted at a spacing of 3.8 m within four rows separated by 10.7 m alleys near Mt Vernon, Missouri (USA). Annual rainfall averaged 1160 mm from 1985 to 2003. Maximum daily temperatures for August averaged 31.8 °C from 1985 to 2002, while minimum daily temperatures for January averaged −5.1 °C. The understory at the time of planting was tall fescue sod. (*Festuca arundinacea* Schreb.). The site is a rocky, upland location. The soil is classified as a Mollic Fragiudalfs (Hoberg silt loam and Keeno cherty silt loam soil series). Herbicides were used to control grass and weeds in the immediate area of the trees for the first 3 years, after which the fescue was allowed to re-colonize the area. At age 9, grass control was resumed in two of the four rows and continued until 1999. Trees growing where the understory grass was controlled had a site index (SI, i.e. tree height at age 25) of 10.5 m in 2001, whereas trees growing in competition with the tall fescue had a site index of 5.5 m in 2001 (Ares and Brauer 2004). Both trees and grass were fertilized in April with about 50 kg N ha^{-1}. Foliar leaf diseases and insects were not controlled. Trees with little or no nut production were periodically removed during the 1990's to maintain an open canopy for the remaining trees.

Significant nut production started in 1987 and nut production was documented on an annual per tree basis from 1987 to 1999 for all trees (Thomas et al. 2003) and for 20 trees in the 10.5 m SI stand through 2003. Data from this site were segregated into three data sets: (1) annual nut data for 17 years (1987–2003) for 20 trees in the 10.5 m SI stand; (2) annual nut data for 13 years (1987–1999) for 80 trees in the 5.5 m SI stand; and (3) annual nut data for 13 years (1987–1999) for 60 trees in the 10.5 m SI. All three data sets contained annual nut yield data but only the 17-year data set contained DBH data, which was collected in the fall of 2002.

Tennessee data sets

Zarger (1946) reported nut yields for 106 native trees for 6 consecutive years (1940–1945) and for 36 trees for 4 consecutive years (1942–1945). Zarger (1946) also reported each tree's average DBH. Only open canopy trees were included in the study. The geographic location of these trees within the Tennessee River valley (USA) was not reported and attempts to find such information have been unsuccessful.

Statistical analysis

Data were analyzed using Excel (Microsoft Corporation 1999) and SAS (SAS Institute 1989). Nut bearing patterns over time were assessed by comparing yields in the second year to the first and indicating an increase or decrease by 1 or −1, respectively. Comparisons between successive years were made in a similar fashion for the entire chronology of nut production per tree. A tree expressing alternate bearing at least 50% of the time had a score of 1 followed by −1 or −1 followed by 1 for at least half of the years in the chronology.

Results

Tree-to-tree variation

The coefficients of variation (CVs) for nut yields were examined as an estimate of tree-to-tree variation. Data from individual trees within each data set were analyzed to determine means, standard deviations and CVs. The CVs for nut yields among trees at the Chetopa averaged about 90% when data from a single year were analyzed (Figure 1). The CVs declined to about 70% when yields were averaged over 2 consecutive years. The CVs averaged about 65% when nut yield data per tree were averaged over 3–5 years. Similar results were found using the 17-year data set from Mt Vernon (Figure 1). The CVs for single year data averaged about 120%. Averaging nut yields over 2 consecutive years decreased the CVs to less than 80%. Averaging nut yields over 3 or 4 consecutive years decreased the CVs to 60–65%. The CVs for nut yield declined further as yields per tree were averaged over an increasing number of consecutive years. A minimum CV of about 50% was achieved when data from all 17 years were averaged.

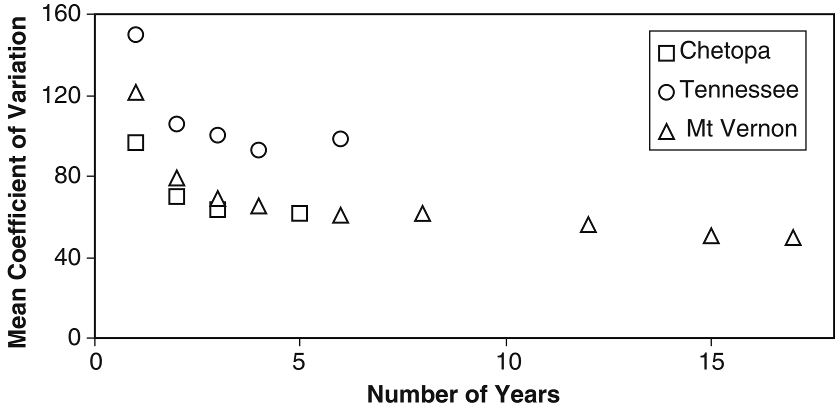

Figure 1. Effects of number of years for averaging data on the coefficient of variations for nut yields of open-canopy black walnut trees (*Juglans nigra*) in southern USA.

The CVs were greater for the Tennessee data set than for the other two. The CVs for annual nut yield data averaged 150%. The CVs declined to about 90% when nut yields were averaged over 3–6 consecutive years (Figure 1). Two subsets of the Tennessee data were also analyzed to examine the effects of DBH on tree-to-tree variation in nut yields. These two subsets represented trees with DBH values similar to those of the trees in Chetopa and Mt Vernon data. The CVs for nut yield data tended to be larger than those from the Chetopa and Mt Vernon data but smaller than those for the complete Tennessee data (data not shown). However, the same trend was observed: the CVs were smaller approaching a finite minimum as nut yields were averaged over an increasing number of consecutive years.

Annual variation

Yields at the Chetopa site had a clear pattern of an alternate bearing pattern (Figure 2a), with odd numbered calendar years having high yields. Nut yields tended to increase with time. A distinct alternate bearing pattern was not observed with either the 4- or 6-year Tennessee data when data were averaged across trees (Figure 2b). The 20 trees in the 17 year Mt Vernon data set were the highest nut producing trees at this site. When averaged across trees for the 17-year record, there was an apparent alternate bearing pattern from 1987 to 1989 and from 1994 to 2001 (Figure 3a). Average annual nut yield data for the other two data sets from the Mt Vernon site indicate two main differences from the 17-year data (Figure 3b): (1) the lack of nut production from 1996 to 1999; and (2) lower yields, except in 1990, when all of trees at the Mt Vernon site had little or no nut yield. When data were averaged across trees for 13-year data set for trees in the 10.5 and 5.5 SI stands, nut yields exhibited an alternate bearing pattern in 1986 through 1988 and in 1994 through 1996 (Figure 3b).

Pattern of nut yields over time by individual trees were examined to more fully explore patterns of annual variations. Sixty-five percent of the trees at Chetopa exhibited alternate bearing over the 5 years (Table 1) and all of these trees exhibited higher yields in 1997, 1999 and 2001 as compared to the proceeding year. All of the trees at Chetopa exhibited biennial alternate bearing pattern at least 50% of the years. A Chi-square test for specific proportion was constructed using alternate pattern of high-low-high-low-high as one category and all other patterns as the other pattern. A Chi-square for specified proportions was 998 (Degrees of freedom $= 1$, $p < 0.0001$), thus indicating that the percentage of trees exhibiting alternate bearing deviated from the expected percentage for random chance.

Tennessee data were subdivided into two sets to examine annual patterns of nut production: (1) trees with 4 years of data; and (2) trees with 6 years of data. Examination of the annual variation in nut yields by individual trees in the 4- and 6-year data set did reveal that a large percentage of the trees tended to exhibit alternate bearing pattern (Table 1). Nut bearing was either sporadic or

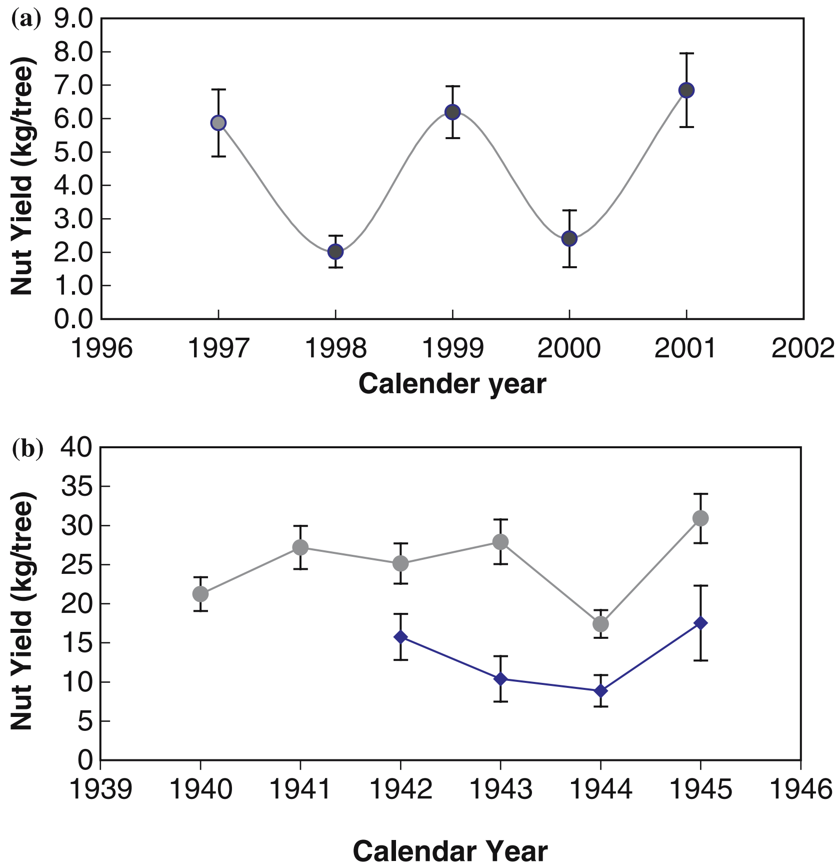

Figure 2. Year to year variation in nut yields for open-canopy black walnut trees (*Juglans nigra*). Data from the Chetopa and Tennessee data sets are in panel a and b, respectively (b). In panel b, squares and triangles represent means of the 6- and 4-year data sets, respectively. Bars represent standard deviations.

lacking a recognizable pattern in only 11.1% of the trees in the 4-year data. Over 40% of the trees exhibited alternate bearing throughout the 4 years. Of the trees consistently exhibiting biennial alternate bearing pattern, approximately half of the trees had the pattern of low yields in 1 year followed by higher yields in the next, while the other half had the pattern of high yields followed by low yields for 1942–1945 (data not shown). A Chi-square test for specific proportion was constructed using alternate pattern of high-low or low-high as two categories, and all other patterns as the third category. A Chi-square for specified proportions was 309.0 (Degrees of freedom = 2, $p < 0.0001$), thus indicating that the percentage of trees exhibiting one of the two alternate bearing patterns deviated from the expected percentage for random chance.

No recognizable pattern of nut bearing was observed in about 2% of the 106 trees in the 6-year Tennessee data (Table 1). Almost half of the trees in the 6-year Tennessee data set exhibited the biennial alternate bearing pattern from 1940 to 1945. The number of trees exhibiting high yields in 1 year followed by lower yields was nearly the same as the number exhibiting low yields followed by higher yields for 1940–1945 (data not shown). A Chi-square test for specific proportion was constructed using alternate pattern of high-low or low-high as two categories, and all other patterns as the third category. A Chi-square for specified proportions was 11,109.0 (degrees of freedom [df] = 2, $p < 0.0001$), thus indicating that the percentage of trees exhibiting one of the two alternate bearing patterns deviated from the expected percentage for random chance.

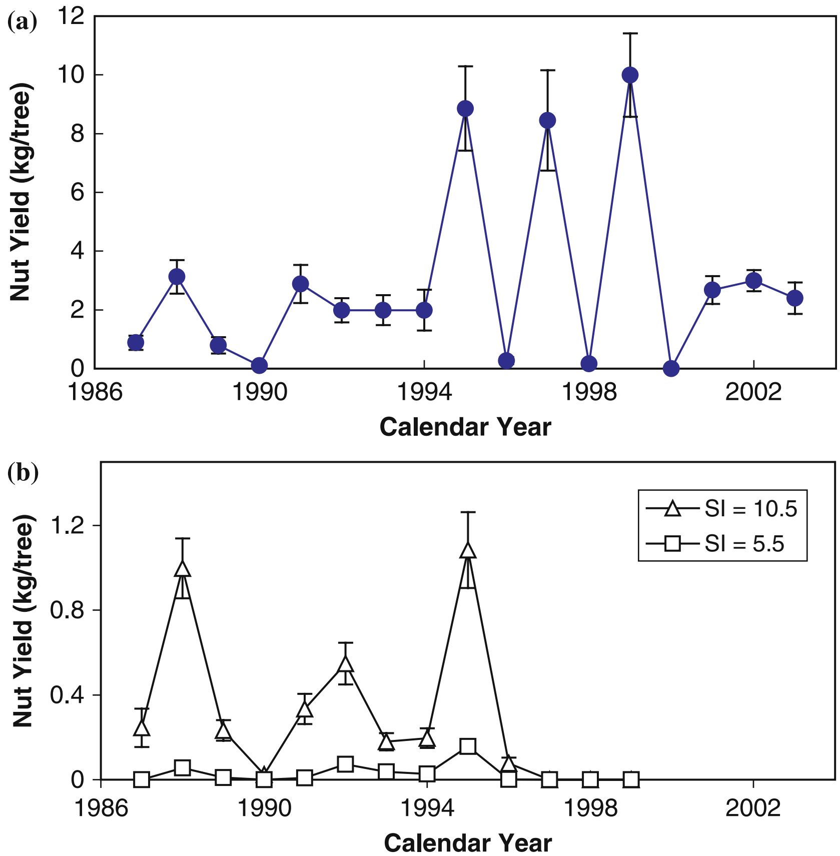

Figure 3. Variations in annual nut yield for open-canopy black walnut (*Juglans nigra*) trees growing near Mt Vernon MO, USA. Data from the 20 trees in the 10.5 SI stand with 17-year record appear in panel a, while data from 60 trees in the 10.5 SI stand (△) and 80 trees in the 5.5 SI stand (□) with a 13-year record appear in panel b.

Over 70% of the trees in the 17-year Mt Vernon data exhibited alternate bearing in at least 75% of the years from 1987 to 2003 (Table 1). However, only 5% of the trees exhibited alternate bearing pattern throughout the 17-year record. In particular, low yields in 1990 tended to disrupt the prior alternate bearing pattern and resumption of the pattern did not occur until 1994 (Figure 3a). Analysis of annual variations in nut yields among the trees of the 5.5 m SI stand indicated that most of the trees (90%) had a sporadic pattern of nut production. Sixty-nine percent of the trees never

Table 1. Percentage of open-canopy black walnut (*Juglans nigra*) trees in southern USA expressing a particular pattern of nut bearing over time.

Location	Chetopa	Tennessee		Mt Vernon		
Number of years	5	4	6	17	13	13
SI of stand				10.5	5.5	10.5
Number of trees	20	36	96	20	80	60
Nut bearing pattern	Percentage of trees expressing pattern					
Sporadic	0.0	11.1	2.1	0.0	90.0	50.0
Biennial alternate bearing 50–74% of year	10.0	0.0	6.3	10.0	0.0	8.3
Biennial alternate bearing 75–99% of year	25.0	44.4	12.5	15.0	6.3	33.3
Biennial alternate bearing 100% of years	65.0		32.2	70.0	3.8	0.0
3- to 4-year cycles of bearing	0.0	44.4	47.9	5.0	0.0	8.3

produced any nuts over the 13-year period and almost 90% of the trees produced nuts in less than 2 of the 13 years. Nut production was observed in at least 5 years in only about 10% of the trees. A low-high pattern of annual variation in nut yields was observed among these trees.

Nut production was sporadic in about 50% of the trees in the 13-year data of the 10.5 m SI stand (Table 1). Nut production occurred in less than 5 years from 1987 to 1999 for the trees with the sporadic yield pattern (data not shown). None of the trees in this data set exhibited alternate bearing throughout the 13 years (Table 1). Over 40% of the trees exhibited alternate bearing in 50–99% of the years. About 8% of the trees exhibited 3- or 4-year cycles with a 3-year cycle of 1 year with very high yields being followed by 2 years of lower yields being the most common pattern in this category (data not shown).

Relationship between DBH and nut yields

A robust relationship between tree DBH and nut yields would help to make better predictions of the economics of black walnut practices. The R^2 for regression equations relating DBH to nut yields using all of available data (i.e. annual nut yields) within a given data set were relatively low, varying from a low of 0.008 for the 17-year Mt Vernon data set 0.164 for the Chetopa data (data not shown). The R^2 for the Tennessee data was intermediate at 0.122 (data not shown).

The R^2 between nut yields and DBH for data collected annually were also relatively low (Figure 4). R^2 tended to be greater for the Chetopa data and the smallest for the 17-year data set from Mt Vernon. However, the R^2 between DBH and nut yield increased when nut yield data were averaged over consecutive years (Figure 4). Maximum R^2 occurred when data were averaged over a minimum of 4 consecutive years.

The Tennessee data set was subdivided into seven DBH classes to investigate the effects of averaging nut yield data over a number of trees with similar DBH. Data from about 20 trees with similar DBH comprised each DBH class. Regression analyses were performed using the average DBH for each class and either 4- or 6-year nut yield mean from each tree within each DBH class. The data were analyzed (Figure 5). The resulting regression equation was:

$$\text{Average nut yield (kg/tree)} = -10.41 + 0.746\ (\text{DBH, cm}), R^2 = 0.985.$$

In comparison, when nut yield data from individual trees were analyzed in a similar manner, the regression equation was:

$$\text{Average nut yield (kg/tree)} = -9.94 + 0.732\ (\text{DBH, cm}), R^2 = 0.40.$$

Thus, averaging data within DBH classes improved the equation's R^2, but had little affect either Y-intercept or slope.

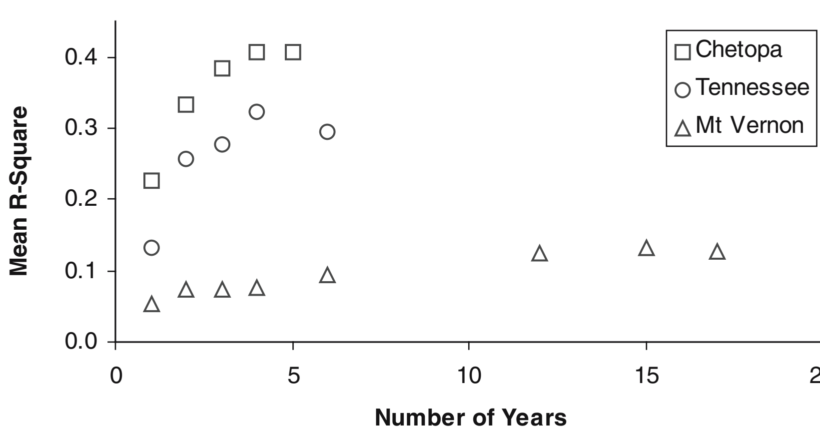

Figure 4. Effects of number of years for averaging nut yields on the predictive value (R^2) of DBH–nut yield relationships for open-canopy black walnut (*Juglans nigra*) trees in the southern USA. Data legend is inserted in the figure.

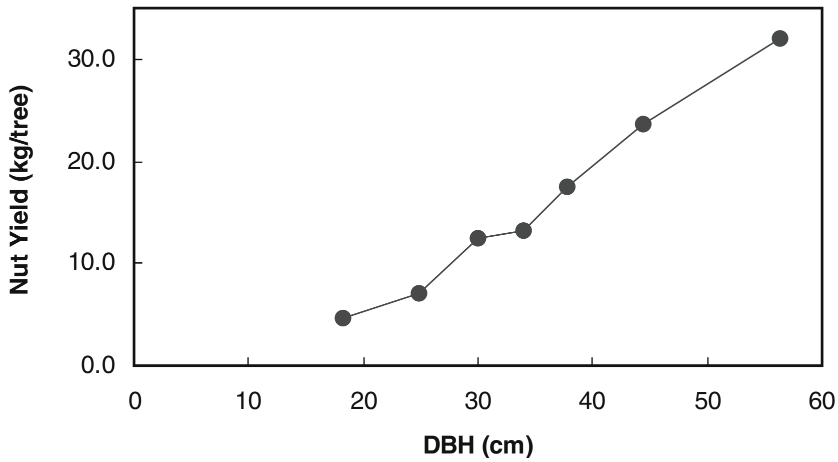

Figure 5. Relationship between DBH and nut yields for open-canopy black walnut (*Juglans nigra*) trees growing in the Tennessee River valley, USA. Nut yields in the Tennessee data set were sorted by DBH. DBH data were averaged over approximately 20 trees within a DBH class. Nut yield data were averaged over 4 or 6 consecutive years.

Discussion

Results from this study will contribute to a database to assess the economics of eastern black walnut practices. Nut yields of individual trees varied considerably over time, as evident by the high CVs for nut yields in each of the studied data sets. Averaging data over at least 2 consecutive years significantly reduced the variability (Figure 1). Such results indicate that data need to be collected for several years to identify the nut yield potential of individual trees. Therefore, landowners and timber stand managers should take observations of nut yields for at least 2 years prior to a selective thinning in order to identify higher producing trees.

The magnitude of the variation in nut yields differed among the three data sets, with the Tennessee data set being the greatest (Figure 1). The greater variation in the Tennessee data set is not surprising since the trees in this data set were from a larger geographical region than the other two data sets. Also, the Tennessee data set includes native trees that probably have high degree of genetic diversity. Jones et al. (1995) have previously reported that the nut yields among native trees varied considerably. Variation in nut yields among trees in the Chetopa and Mt Vernon data set were similar except when annual data are compared. Such results may seem surprising because the variation in nut yields of native trees appears to be similar to that of trees of improved genotypes. The selection criteria for the development of improved genotypes of eastern black walnut have focused primarily on nut characteristics (Reid et al. 2004), for example, percent of the nut as kernel, frequency of kernel quarters and halves after cracking, etc. Therefore, there has been little selection pressure for nut yield in the development of these improved genotypes. In addition, there is probably substantial genetic diversity among individuals within an improved genotype, because at present, only the genetics of the maternal parent is known for seed sold as an improved genotype.

About half of the trees in the analyzed data sets exhibited alternate nut bearing patterns, i.e. high yield in 1 year followed by a year of lower yields (Table 1). Trees within Chetopa and Mt Vernon data sets exhibited the same pattern of alternate bearing, i.e. all the trees in the data set had high yields in the same years and followed by low yields. The proportion of trees in the Tennessee data set exhibiting pattern of low yields in one year followed by high yields in the next year was about the same as high yields followed by low yields. The Tennessee data set was unique, because only this data set included results from multiple locations (Zarger 1946). One possible explanation for such a difference between the Tennessee data and the other two is that local climatic conditions affected biennial yield patterns. Previously, Ponder and Jones (2001) reported that applications of N, P and K encouraged high nut yields in the fifth year of their study, which should have been a low-yield year if the biennial pattern had persisted.

Nut yields could be predicted with varying degrees of certainty from DBH data. The maximum R^2 for the relation between DBH and nut yields for data from individual trees was 0.40. Therefore, over half of the tree-to-tree variation in nut yields was affected by characteristics other than tree size and may include genetics, location, climate, and other factors. The best prediction of nut yields was achieved when nut yield data were averaged over at least 4 consecutive years and DBH values were averaged. Such results indicate that nut yield predictions for a tree stand over several years will be superior to predictions for individual trees in a given year. Nut yield predictive equations with a high degree of accuracy have been developed for pecans growing in distinct geographic regions (Sparks 1997; Wright et al. 1990). These equations are most useful in predicting final nut yields after flowers have been pollinated. Terms in these predictive equations tend to include: (1) existing nut count; (2) days from bud break; (3) low or high crop year; and (4) tree growth. Both of these equations used trunk circumstance as a measure of tree growth. These predictive equations can account for almost 90% of the variation in nut yields between different stands of trees. This level of accuracy is needed for pecan growers to make decisions regarding marketing strategies for the present year's crop. However, such a high level of accuracy is probably not needed to aid landowners in their decisions regarding establishing walnut plantings. Results in this report indicate that the construction of predictive equations for walnut nut yields with a modest level of accuracy (R^2 = 0.40) is possible especially when tree growth and yields are averaged over several years and number of trees. These results also indicate that these predictive equations for black walnut yields may need to include terms for stand location, low or high crop year, and climatic conditions to increase their accuracy.

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